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Charlie N. Barron, Robert W. Helber, Gregg A. Jacobs, Murat Gunduz, Pete Spence

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14. ABSTRACT
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15. SUBJECT TERMS
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Acoustic impact of short-term ocean variability in the Okinawa Trough

C.N. Barron, R.W. Helber, G.A. Jacobs
Naval Research Laboratory
NRL Code 7320
Stennis Space Center, USA

M. Gunduz
Center for Ocean-Atmospheric Prediction Studies
Florida State University
Tallahassce, FL USA

P. Spence
QinetiQ North America
Technology Solutions Group—PSI,
Stcnnis Spacc Center, MS, USA

Abstract*- The impact of short-term ocean variability on acoustic transmission loss (TL) is examined in the nature run of an observation system simulation experiment (OSSE) centered on the Okinawa Trough in the western North Pacific. Range-dependent examinations of TL in the upper ocean show the impact of variability as it modifies the sonic layer depth and thickness of the surface duct. Short term variations in the marine environment are shown to have potentially significant impact on acoustic propagation, particularly for applications using active sonar. We examine case studies highlighting the effects of three types of phenomena: diurnal warming, typhoon-induced mixing, diurnal warming, and internal waves. These phenomena were identified as important in the OSSE study area during an extensive Navy data collection effort during the summer and fall of 2007. Publically available observations are used to evaluate the fidelity of the nature run, which then serves as the standard for both range-dependent TL computations and comparisons of ocean prediction alternatives. Some of the alternatives do not represent short-term ocean variability. Thus the case studies reveal the types of errors that arise when acoustic calculations fail to account for a sufficient spectrum of environmental influences. TL differences in the variable environments demonstrate acoustic prediction benefits provided by increasingly capable Navy ocean models.

I. INTRODUCTION

Naval Operational Sound Speed Prediction (NOSSP) is a key function for the Naval Oceanographic Office (NAVOCEANO) in support of anti-submarine warfare (ASW). These predictions should capture environmental variability that can significantly affect acoustic transmission loss (TL). In particular, sound speed fields must capture the short-term ocean variability where it is found to have potentially large impact on TL and acoustic transmission range. Manifestations of this variability are evident in and around the Okinawa Trough during July-October 2007, coinciding with an extensive Navy-supported data collection effort. We assume that the phenomena identified as contributors to acoustically-significant environmental variability in this region have analogues in other regions of the world. While the Okinawa Trough is one of the regions of interest, NAVOCEANO is tasked with providing sound speed predictions for areas all over the world. Planning and conducting ASW operations requires sound speed predictions that sufficiently represent the ocean environment in any of these areas. In particular, the products used for NOSSP must account for higher frequency variability in order to identify exploitable windows of opportunity, locations where local conditions are temporarily favorable for extended acoustic transmission and therefore increased detection capability. Similarly, the products must also distinguish intervals and locations where detection ranges are reduced. With this knowledge, mission planning can focus on exploiting favorable regions with fewer resources where possible and avoid conditions where detection is more difficult. If it is not possible to avoid less favorable operating environments, accurate predictions are required to assess the impact on detection systems and the effectiveness of deploying additional detection assets. For effective mission planning, NOSSP must accurately resolve the time and space scales on which the ocean changes between favorable and unfavorable conditions for long-range acoustic transmission.

The impact of short-term ocean variability on TL is examined through an examination of the nature run developed for an observation system simulation experiment (OSSE) centered on the Okinawa Trough in the western North Pacific. Range-dependent examinations of TL in the upper ocean show the impact of variability as it modifies the sonic layer depth (SLD) and thickness of the surface duct. Short term variations in the marine environment are shown to have potentially significant impact on

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acoustic propagation, particularly for applications using active sonar. We examine case studies highlighting the effects of three types of phenomena: diurnal warming, typhoon-induced mixing, diurnal warming, and internal waves. Each of these processes contributes significant short-term variability in the Okinawa Trough region during the summer and fall of 2007. Publically available observations are used to evaluate the fidelity of the nature run, which then serves as the standard for both range-dependent TL computations and comparisons of ocean prediction alternatives. Some of the alternatives do not represent short-term ocean variability. Thus the case studies reveal the types of errors that arise when acoustic calculations fail to account for a sufficient spectrum of environmental influences. TL differences in the variable environments demonstrate acoustic prediction benefits provided by increasingly capable Navy ocean models.

Section II describes several presently or previously operational prediction systems which are examined as candidates for the OSSE nature run. Section III defines the acoustically-relevant evaluation criteria and examines performance of the nature run alternatives. Section IV discusses phenomena producing short-term variability that is inadequately represented in the less capable prediction alternatives. Section V summarizes the results and describes planned OSSE investigations.

II. NATURE RUN ALTERNATIVES

The validity of an OSSE begins with defining the nature run, the fundamental ocean model run that is taken to represent the true ocean state. The results of the nature run can be sampled at any time and location over the course of the experiment, thereby enabling the ocean to be freely measured by an infinite variety of observing systems. These or other results may be assimilated using a range of approaches as alternative systems for predicting the ocean environment. The relative performance of the experimental alternatives is assessed by comparing the predictions of each to the corresponding conditions in the nature run.

Six Navy ocean environment models are considered as alternatives for the nature run: Generalized Digital Environment Model (GDEM) 3.0 climatology[1], Modular Ocean Data Assimilation System (MODAS) synthetic profiles[2], Navy Coupled Ocean Data Assimilation (NCODA) multivariate optimal interpolation[3], versions 2.5 and 2.6 of the Navy Coastal Ocean Model (NCOM)-based Global Ocean Forecast System (GOFS)[4], and a 3-km scale nested relocatable (RELO) NCOM. Each of these is presently or previously operational, potentially preferred for a particular class of applications, and thus a possible source of sound speed for estimates of acoustic transmission. Three, GDEM, MODAS, and NCODA, are statistical products, and the other three are dynamic forecasts from NCOM. GDEM is a climatology based solely on historical observations, while MODAS additionally uses recent remote sensing and NCODA combines remote and in situ observations. GOFS 2.5 assimilates the MODAS synthetics, while GOFS 2.6 and RELO assimilate global and regional NCODA analyses, respectively. RELO uses boundary conditions from GOFS 2.6. RELO and NCODA are prepared on the regional domain shown in Fig. 1, while the other products are resampled to this domain from their global grids.

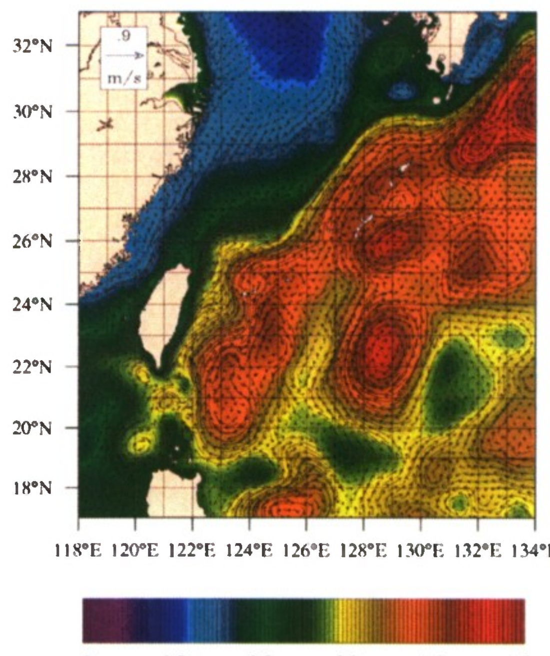

Fig. 1 Surface currents superimposed on SSH, both from RELO NCOM and averaged over 7-8 October 2007. Both the RELO NCOM and regional NCODA runs use this domain.

III. EVALUATION OF ALTERNATIVES

While the nature run is not expected to perfectly correspond to all aspects of the true ocean, our confidence in the nature run is increased if it shows good agreement with ocean observations and realistic representation of ocean processes and variability. We use publically available observations to evaluate the performance of these candidate ocean predictions. The nowcast and forecast fully assimilative NCOM nest is found to agree most closely with the assimilated and un-assimilated observations, increasing our confidence in both the representativeness of the nature run and the effectiveness of nested NCOM as used in daily Navy operations.

Because this article is concerned with the influence of variations in the ocean on acoustic transmission, evaluations focus on one aspect of transmission that is clearly sensitive to such variations: acoustic transmission that is potentially confined to a surface duct[5]. The surface duct may be characterized in terms of its SLD or minimum cutoff frequency (MCF). SLD is the vertical distance from the surface to a subsurface sound speed maximum. Sound speed often increases

monotonically from the surface to the SLD, but, as shown in Ref. [6], the first local minimum is not necessarily representative of the effective SLD. Overall ducting may be insensitive to small variations in the sound speed profile or superseded by a deeper local maximum. MCF is inversely proportional to SLD, so deeper sonic layers have a lower MCF and thus trap a larger frequency range in the surface duct. Frequencies above the MCF have approximately cylindrical transmission with loss proportional to the range squared, while transmission at lower frequencies is approximately spherical with loss proportional to the range cubed. Thus the horizontal transmission range for signals above the MCF is generally much longer than the range for lower frequencies. As a consequence, signals at frequencies near the MCF are most sensitive to variations in SLD.

Mixed layer depth (MLD) is a property of the water column that is in many ways a density-based analog of the sound-speed-based SLD. In general MLD is the depth above which the temperature (T) and salinity (S), and thus density, of the water column are well mixed. Various formulations have been proposed to define this transition depth, ranging from identifying the first depth from the surface that shows any curvature from isothermal[7] to identifying a depth that shows a deviation in temperature or density beyond a certain threshold[8]. For this paper, transitions identified only by deviation above a temperature threshold are designated as the isothermal layer depth (ILD), reserving the MLD designation for deviations of density following the temperature-equivalent offset as in Ref. [8]. Often MLD and SLD are treated as equivalents, but this may not hold in cases where T and S change independently, as the sensitivities and relationships between sound speed and T or S differ from the sensitivities and relationships of density[6]. Accuracy of ILD, MLD, and SLD are used as proxies for accurate acoustic transmission.

Table 1 shows root mean squared error (RMS) and mean bias (model-observation) for the alternatives relative to 294 publically available profiles from September-November 2009 (Fig. 2). These profiles have been deemed sufficient to resolve MLD and SLD by the quality control procedures described in Ref. [6]. GOFS 2.6 has the best overall results using these observations. However, this comparison is over a relatively small number of observations; comparisons with an order of magnitude more Navy observations (not shown) indicates more clearly that RELO has the smallest errors in representing the true ocean and relatively better performance for the models over analyses. GOFS 2.6 and RELO NCOM do perform the best overall. Of the candidates for the nature run, RELO has among the smallest bias and RMS error in these acoustically important metrics. It also has the most comprehensive representation of processes important in the Okinawa trough, from smaller spatial scales to including tides to better data assimilation. For these reasons we select the RELO as our nature run for future OSSEs and as the basis for evaluating the impact of short-term variability in the Okinawa Trough region.

IV. Short-Term Variability

Our acoustic case studies focus on one aspect of transmission that is clearly sensitive to short-term ocean variations: acoustic transmission that is potentially confined to a surface duct. The surface duct may be characterized in terms of its SLD or minimum cutoff frequency (MCF) [6]. SLD is the vertical distance from the surface to a subsurface sound speed maximum. The first local maximum is not necessarily representative of the effective SLD, as overall ducting may be insensitive to small variations in the sound speed profile or be superseded by a deeper local maximum. MCF is inversely proportional to SLD, so deeper sonic layers have a lower MCF and thus retain a larger frequency range in the surface duct. Frequencies above the MCF have approximately cylindrical transmission with loss proportional to the range squared,

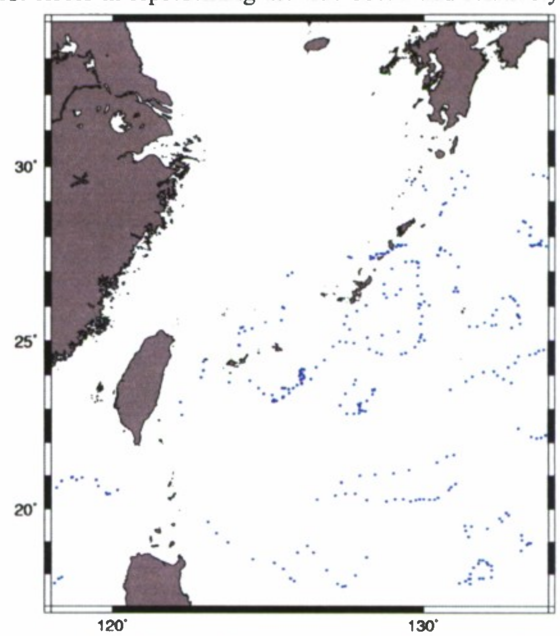

Fig. 2 Locations of all public profile observations from August to October 2007 used in this study to evaluate output of different generations of operational products.

TABLE I

Statistics showing relative agreement between acoustically-relevant water column properties calculated from model analyses and public observations in the Okinawa Trough region over 1 August – 31 October 2007.

	MLD (m)		ILD (m)		SLD (m)		BLG ((m/s)/100m)	
	RMS	BIAS	RMS	BIAS	RMS	BIAS	RMS	BIAS
GDEM 3.0	35.16	-5.92	20.75	-10.56	24.70	-20.85	1.52	-1.24
MODAS	40.00	-9.33	23.46	-15.67	26.73	-24.09	1.39	-1.18
GOFS2.5	34.65	-5.26	19.60	-10.63	14.47	-7.32	0.92	-0.40
GOFS2.6	33.72	0.06	16.60	-5.89	12.82	-5.05	0.77	-0.26
NCODA	50.04	-26.87	21.95	-11.34	15.27	-10.53	0.89	-0.67
RELO	34.95	-6.47	17.60	-6.67	12.82	-5.05	0.83	-0.41

while transmission at lower frequencies is spherical with loss proportional to the range cubed. Thus the transmission range for signals above the MCF is generally much longer than the range for lower frequencies. As a consequence, signals with frequencies near the MCF are most sensitive to variations in SLD.

The impact of short-term environment variations as represented by RELO is shown in select sections of transmission loss determined using range-dependent calculations in a standard Navy parabolic equation Range dependent Acoustic Model (RAM), where acoustic transmission is simulated using a finite difference Pade′ series calculated outward from the source [9]. Similar calculations were presented in Ref. [6]. Minimal smoothing has been applied to the output to eliminate the unrealistic fine structure inherent in calculations with a single source frequency. The simulations run frequencies of 600 Hz, representing a passive detection case, or 3000 HZ, representing an active detection case, with the sound source at 10 m.

Diurnal warming, referred to as the "afternoon effect," has long been recognized as an important source of variability on short time scales. It occurs under conditions of low wind speed and high surface heating, where warming from the surface produces a surface stratification. If the layer were previously well mixed, the stratification would form above the mixed subsurface. Early studies focused on the interaction between the diurnal thermocline and the mixed layer[10], with subsequent attention more focused on air-sea exchange and the influence on atmospheric processes[11]. Global distributions from studies of diurnal warming show a high degree of variability over the year, with instances of large amplitude diurnal warming (>0.5°C) most common in the northern Indian Ocean, Mediterranean Sea and Black Sea but occurring over most of the ocean[12]. For acoustics this diurnal warming produces what is commonly called the afternoon effect, where the top of the night-time isothermal surface layer is warmed. The surface duct in which acoustic waves are refracted upward to reflect from the surface is transformed into a narrower subsurface duct with downward refraction at the surface that produces shadow zones near the surface where acoustic energy is refracted away from the receiver. The afternoon effect is well known but not resolved by climatologies or daily averages; it requires models such that accurately represent the time evolution of the surface boundary layer.

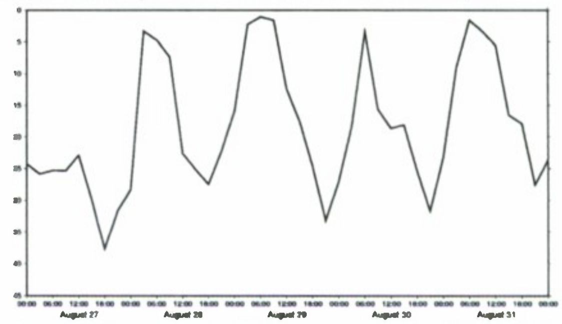

Fig. 3 MLD (m) from the RELO run extracted at 24°N, 123°E. MLD ranges from a maximum in the morning (1800-2100 UTC or 0200-0500 local time) to a minimum in the afternoon (near 0600 UTC or 1400 local time) as warming increases stratification during the day and cooling reduces it at night.

The effects of intense August insolation are evident in an upper ocean time series extracted near Taiwan, which shows a diurnal variation in MLD with afternoon MLD minima separating deeper morning and evening values (Fig. 3). 3000 Hz transmission ranges exceeding 30 km in the morning and evening contrast with afternoon ranges closer to 5 km (Fig. 4). These short term changes due to diurnal warming would cause an active search effort with a near-surface source and receiver to be much more efficient in the morning than in the afternoon.

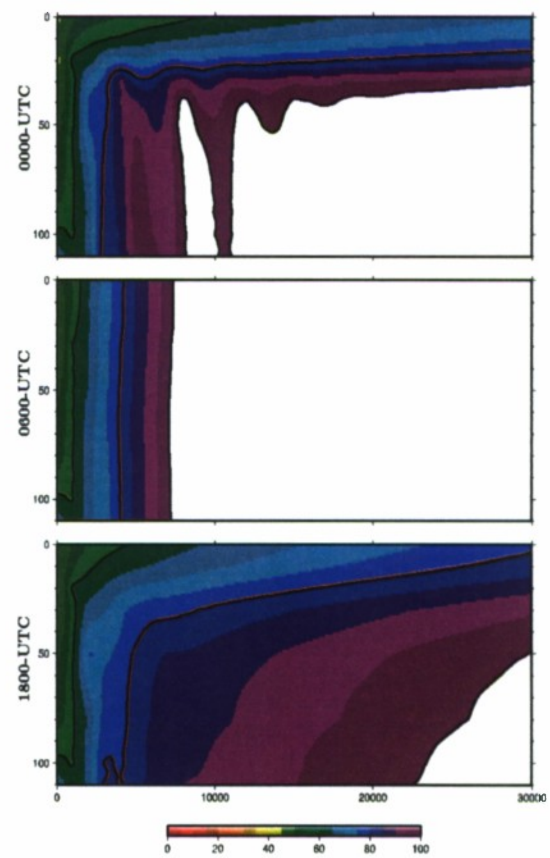

Fig. 4 Transmission loss (dB) on 30 August 2007 as a function of range (km) over depths from 0-110 m for a 3000 Hz source at 10 m along a section northeast of Taiwan. The 80 dB loss contour is highlighted to designate a standard transmission range. Diurnal warming reduces ranges in the afternoon, 0000 UTC or 1400 local time, hence, the "afternoon effect."

Typhoon-induced mixing is an extreme example of the effect of wind-driven mixing on mixed-layer depth. Prior studies have examined the effects of this mixing on the boundary layer for Hurricane Dennis[13] and mixed-layer below Hurricane Gilbert[14]. Hurricane impact on SLD or acoustic transmission was not considered. Four very strong typhoons cross near Taiwan or the Okinawa Trough during the OSSE study, contributing to increases in the overall regional MLD that persist long after the storms pass. Track and intensity details are available from the annual report of the Joint Typhoon Warning Center[15], which rated three as super-typhoons with sustained surface winds reaching 130 knots. The fourth storm was only 5 kt. short of similar super-typhoon status. Thus the influence of strong typhoons is a common late-summer occurrence in the Okinawa Trough region.

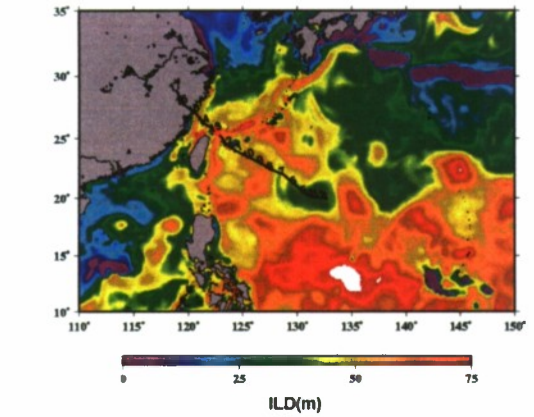

Fig. 5 Isothermal layer depth forecasts for 0600 UCT 18 September 2007 from GOFS 2.5, the global operational system during this time frame. The ground track of Super Typhoon Wipha is labeled at 6-hour intervals along a track just over four days long. With sustained surface winds of 130 kt, Wipha was near maximum strength as it passed north of Taiwan.

The impact of wind-induced mixing from super-typhoon Wipha is demonstrated in September over a section at 26°N. The ground track for Wipha is shown in Fig. 5, and the associated 3000Hz transmission loss in Fig. 6. In this section northeast of Taiwan, wind-induced mixing from Nari the week before is not strong enough to create a surface duct sufficient for acoustic transmission at 3000 Hz. Wipha manages to produce a sufficiently large duct for most of September 18, as the response to typhoon-induced mixing increases transmission ranges of less than 5 km to over 20 km. Restratification and short ranges return as Wipha makes landfall as the duct rapidly breaks down late on September 18.

Internal waves are a third category of short term variations which influence the acoustic environment in the western North Pacific. As they propagate through a region, internal waves modulate the background state, changing sonic layer and thermocline depths. Internal waves occur in all parts of the global ocean but are particularly prominent in the South China Sea and Philippine Sea where they radiate from the Luzon Strait[16]. They also play a significant role in the Okinawa Trough and in much of the East China Sea[17].

As we considered diurnal warming in August and typhoon mixing in September, the effects of internal waves are examined in mid October a few days after the landfall of Super Typhoon Krosa on 8 October. Figure 7 shows temperature from RELO at 100 m. Internal waves are evident in the bands of crests and troughs emanating from the Luzon Strait south of Taiwan. Since NCOM in RELO is a hydrostatic model, it does not represent the full dynamics controlling the detailed evolution of internal waves, but its tides and dynamics are sufficient to represent their gross behavior.

The effects of this semidiurnal modulation are evident in a section east of the Luzon Strait, at 21°N, 122.5°E-122.7°E. Transmission loss is again calculated using sound speed from RELO. Since MLD has generally increased from August through October, the surface duct is now thicker and the passive detection case with a 600 Hz acoustic source at 10 m replaces the 3000 Hz source examined previously. Transmission ranges are again defined relative to an 80 dB FOM. Transmission ranges below 5 km at 0000 UTC on 12 October 2007 begin to increase to a peak of over 20 km at 1200 UCT on 13 October, only to fade back to shorter

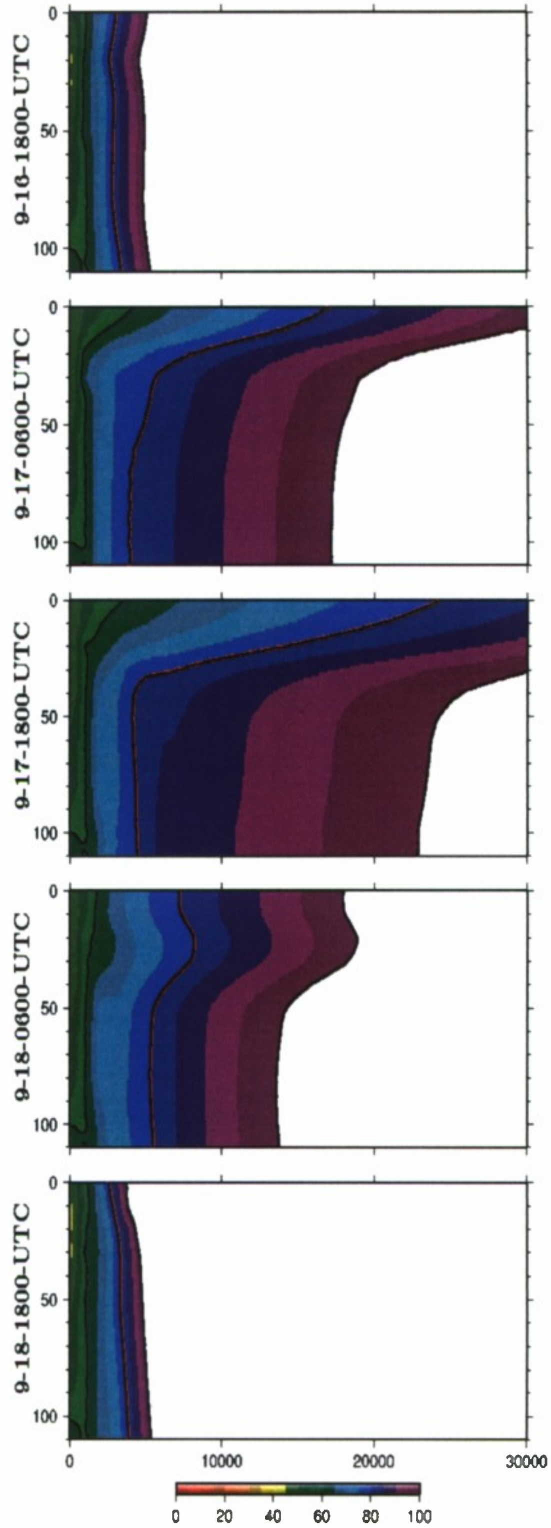

Fig. 6 The impact of Typhoon Wipha seen in transmission loss (dB) as a function of range (km) over depths from 0-110 m for a 3000 Hz source at 10 m depth. The section at 26°N, 123.5°E-123.7°E uses sound speed from RELO.

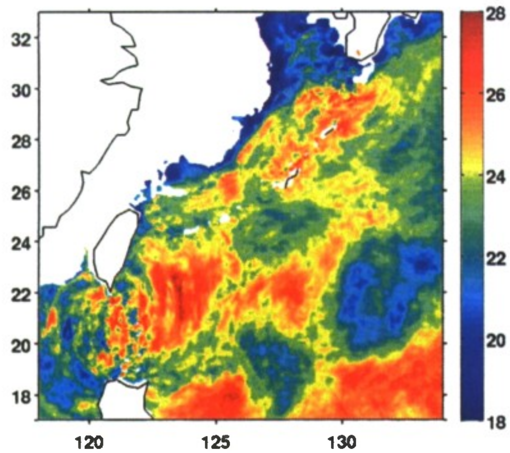

Fig. 7 Temperature at 100 m from RELO on 1800 UTC 12 October 2007. Crests and troughs of internal wave packets are evident emanating from the Luzon Strait.of Taiwan.

ranges on 14 Octobcr. This pulse is modulated by the semidiurnal internal tides to produce local rangc maxima at 12-hour intervals, where

transmission ranges at 0000 UTC and 1200 UTC are longer than their counterparts 6 hours later. The internal tidc combines with other processcs to produce short-term variations that significantly affect acoustic modeling.

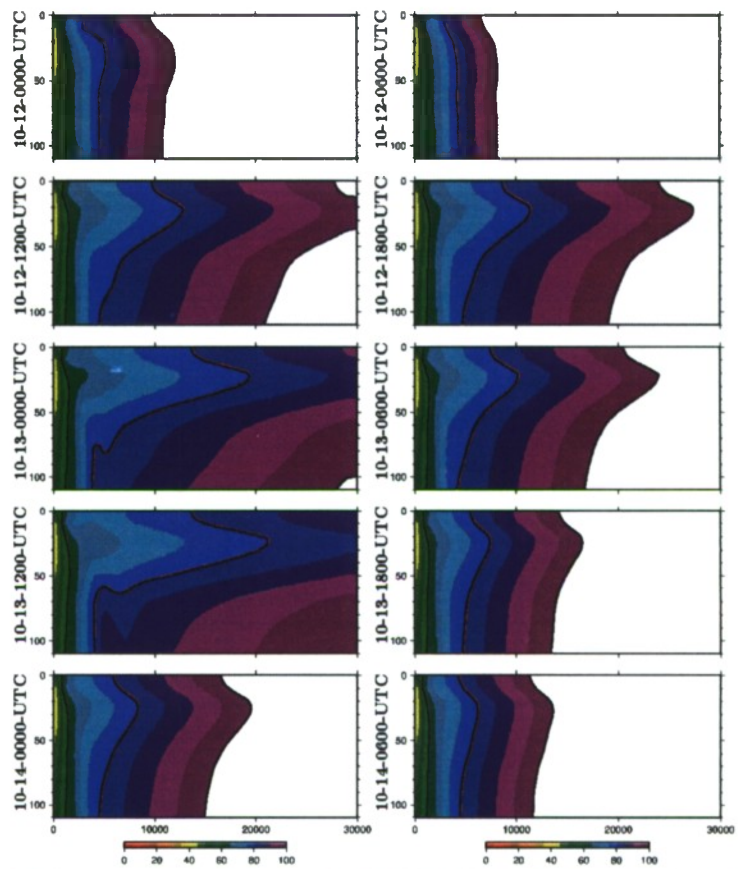

Fig. 8 The impact of internal waves from the Luzon Strait seen in transmission loss (dB) as a function of range (km) over depths from 0-110 m for a 600 Hz source at 10 m depth. The section at 21°N, 122.5°E-122.7°E uses sound speed from RELO. A pulse of deeper SLD and longer transmission ranges that peaks on 13 October is modulated by the semidiurnal internal tides to produce local range maxima at 12-hour intervals.

V. CONCLUSION

In the three months covered by the survey, cases are identified that reveal the influence of diurnal warming, typhoon-induced mixing, and internal waves. Diurnal warming is shown to be important during a period in August when high insolation and low wind speeds cause an afternoon cffect, where restratification during the day sufficiently reduces the surface duct so that it no longer traps a 3000 Hz signal reprcsentative of an active sonar case. Four strong typhoons cross the Okinawa Trough region between August and October 2007, leading to overall increases in MLD as well as shorter term events that create exploitable surface ducts lasting onc or more days, depending on the balance between mixing processes that build a duct and advection or insolation that act to brcak thc duct back down. Focusing on September, the results of the 3000 Hz active sonar case are shown to be sensitive to typhoon induced mixing. Finally, deeper mixed layers resulting from the overall increase in MLD from August to October allow consideration of a 600 Hz passive sonar case in October, in which internal tidcs from the Luzon Strait are shown to modulate the sound speed environment such that peak transmission ranges of 20 km are reduced by 50% in a modulation with semi-diurnal frequency. Thus short tcrm variations in the marine environment can have significant impact on acoustic propagation, in both active and passivc sccnarios. The latest capabilities of the global and regional systems, particularly those combining dynamic response to the wind with assimilation of adequate ocean observations, provide more accurate acoustic predictions that are better able to rcsolve acoustically-significant short term variations in the Okinawa Trough environment.

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